Studies of multi-nucleon transfer reaction with Improved QMD model

I) Introduction

II) Systematic studies of multi-nucleon transfer reactions with Improved Quantum Molecular Dynamics model

III Discussion

Zhuxia Li

China Institute of Atomic Energy

Collaborators: Kai Zhao, Ning Wang, Yingxun Zhang, Tian Junlong, Qingfeng Li, Xizhen Wu

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I. Introduction

deep-inelastic reaction
strong-dumped reaction   different term same meaning
multinucleon transfer reaction

Common understanding

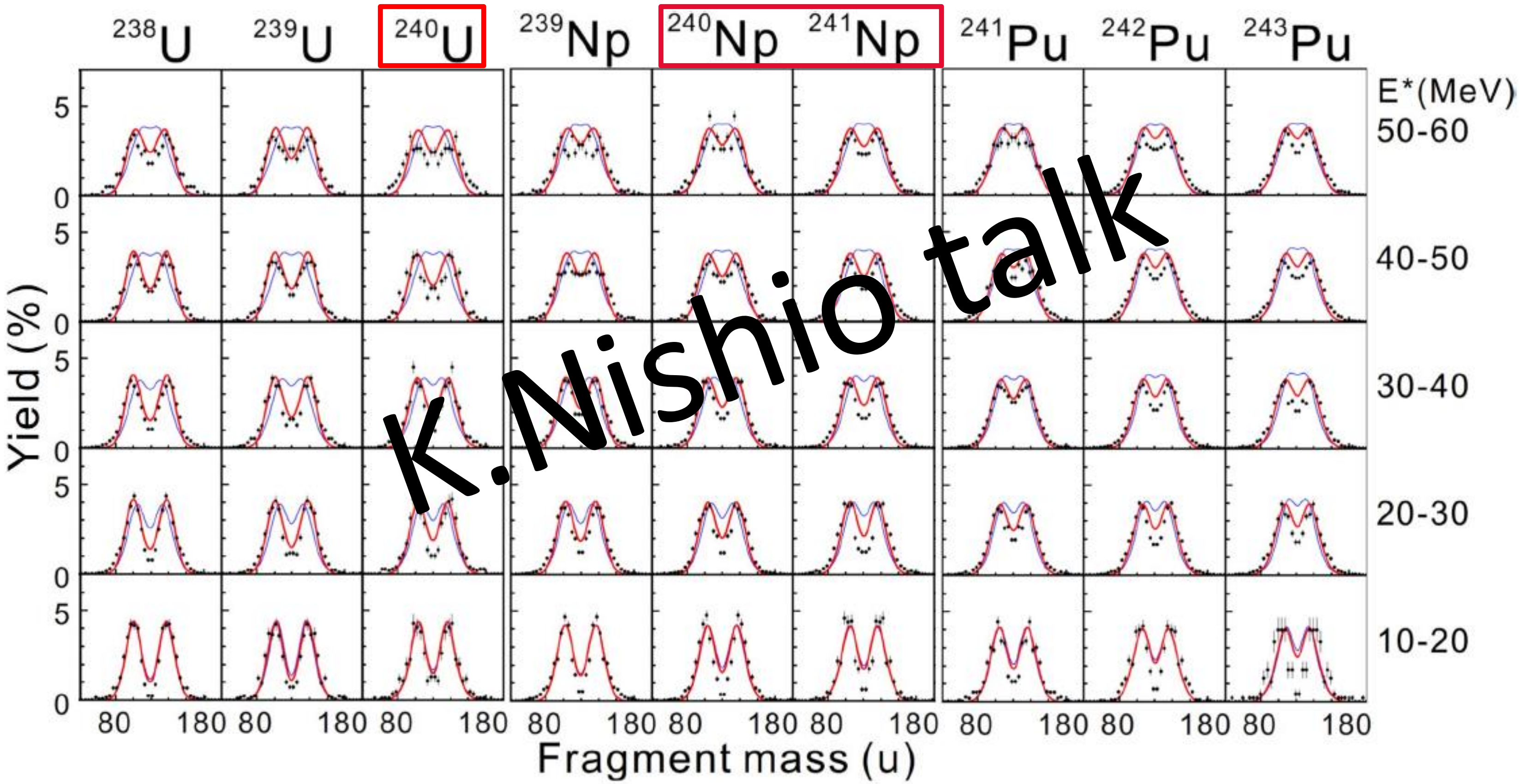
Multinucleon transfer reactions are of great importance

- Important tool for studies of nuclear structure, nucleon correlation, nuclear reaction and nuclear fission
- Efficiency approach for producing new neutron-rich nuclei
- Prospective approach for synthesizing SHN

A powerful tool for studying fission of exotic neutron-rich nuclei

Example

FFMD generated from MNT channels of $^{18}O + ^{238}U$ reaction

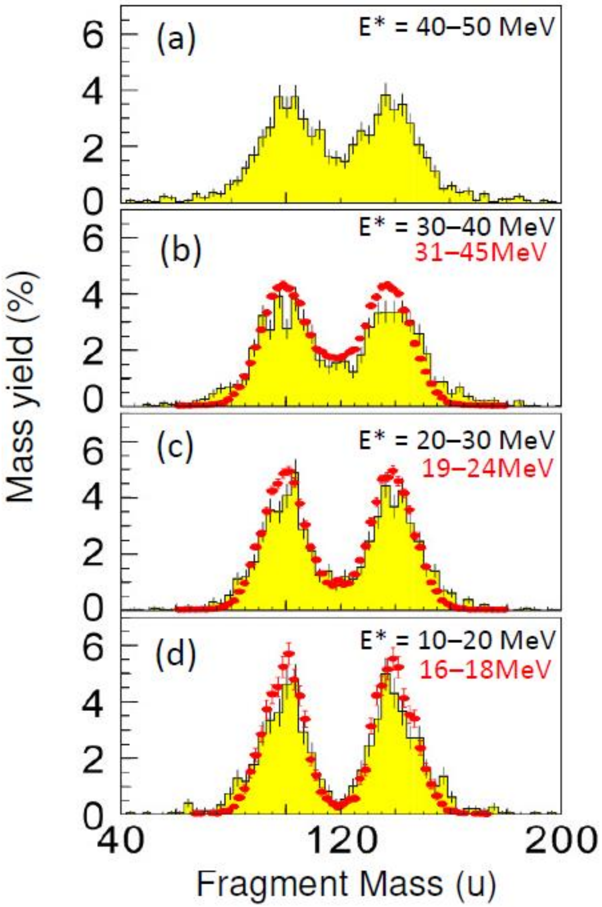


^{240}U, $^{240,241}Np$ was first time measured

Facility of JAEA, E_{lab}=157–162MeV

K. Nishio, K. Hirose, etal., EPJ Web of Conferences **163, 00041 (2017)**

Important tool for study fission



Beam energy 157 MeV

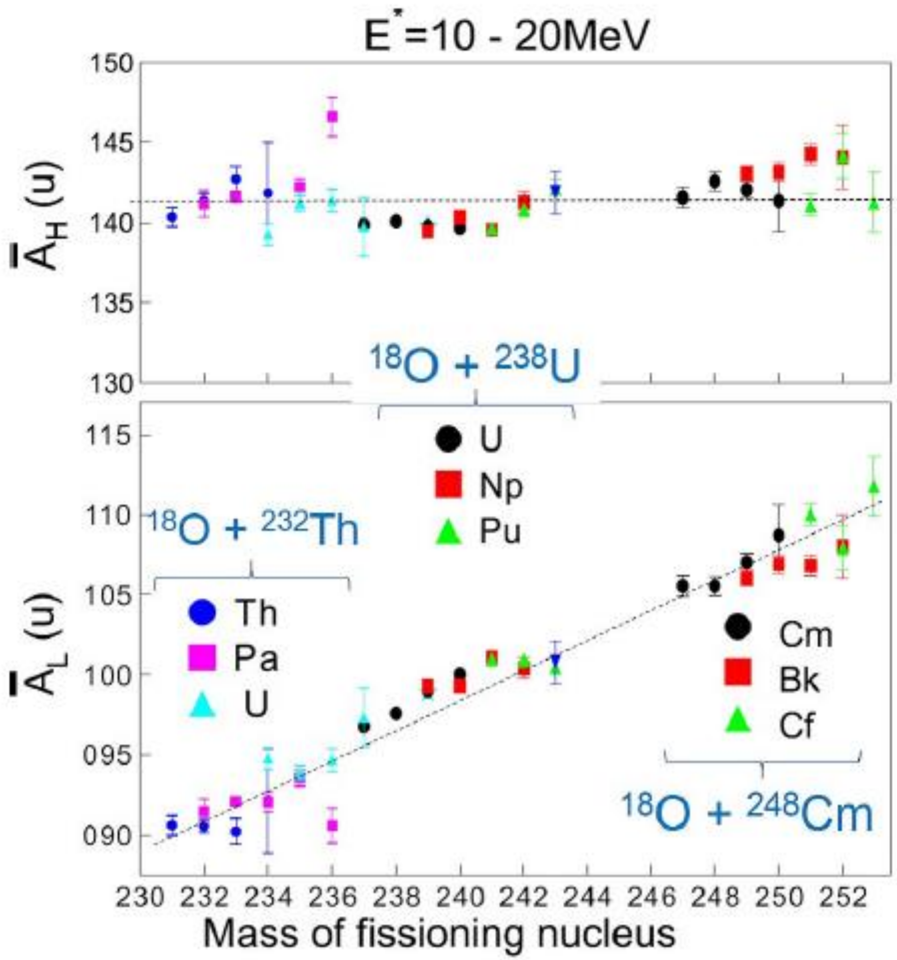
$^{238}U(^{18}O,^{17}O)^{239}U$

Red dots neutron induced fission on ^{238}U

Both agree well

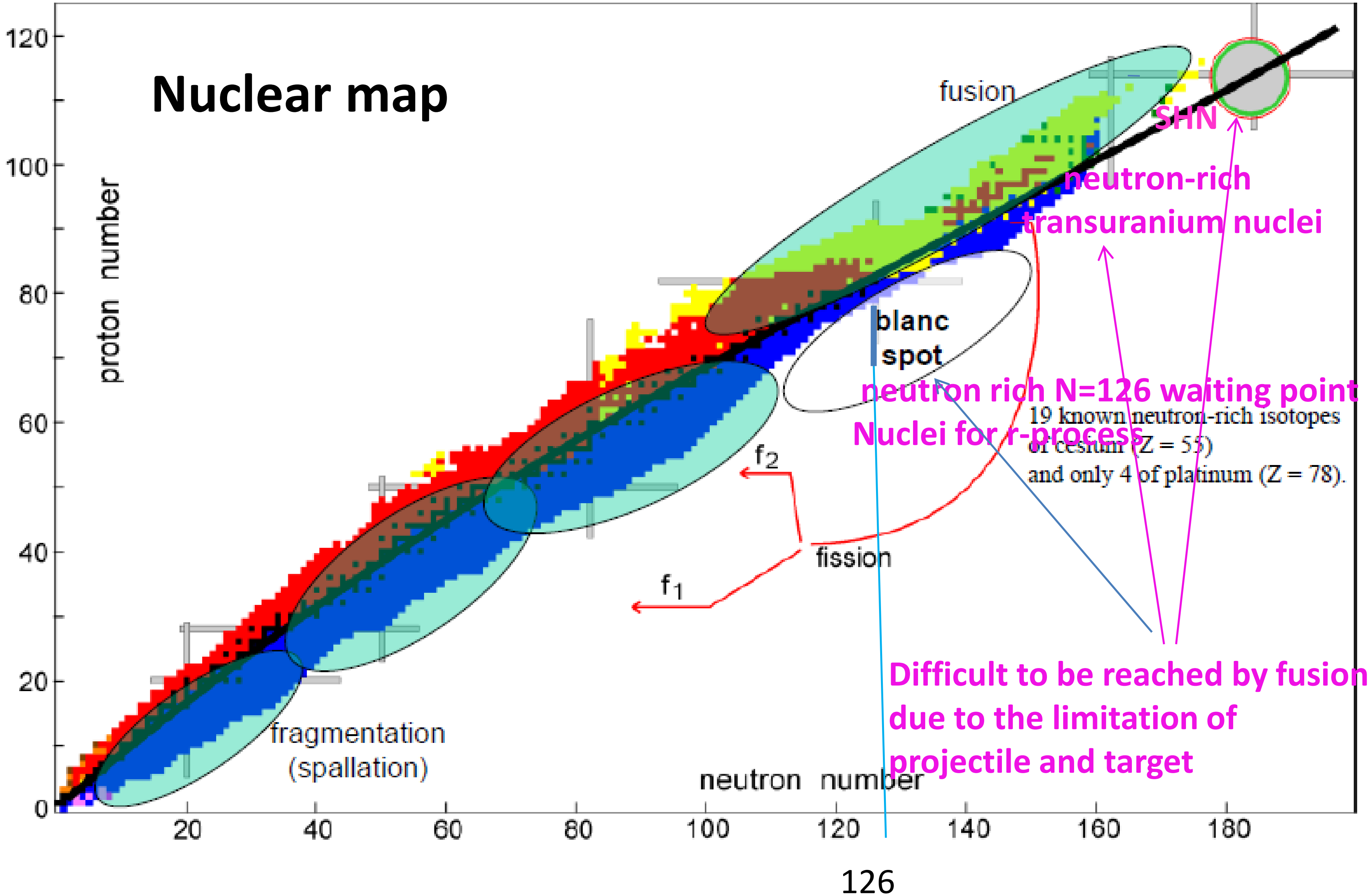
EPJ Web of Conferences **163, 00041 (2017)**

Many fission systems have been generated



Center of light and heavy fragment groups A_L *and* A_H *as*
a function of mass of the fissioning nuclei in excitation fission of 10<E<20MeV.
Data are obtained from reactions of 18O+232Th,238U and 248Cm

MNT Powerful tool for producing neutron-rich nuclei and prospective method for synthesizing SHN



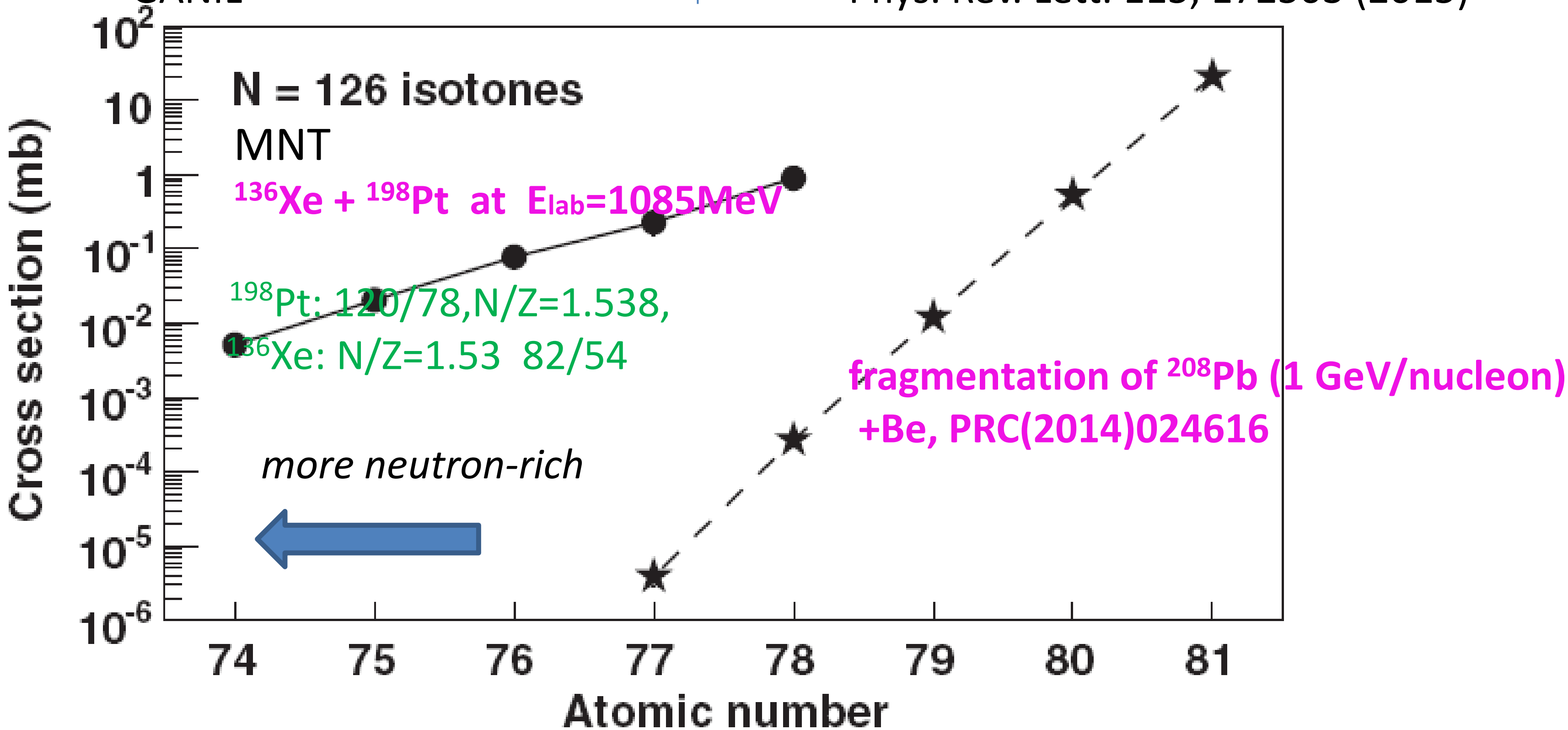
MNT reactions have been applied to produce
new neutron-rich isotopes from light to trans-uranium nuclei

MNT especially useful for producing exotic neutron-rich nuclei
choose optimal reaction condition, such as projectile-target combinations and beam energies

Optimum method for producing Z<78,N=126 neutron-rich nuclei

Direct measurement both A and Z
GANIL

Y. X. Watanabe, *et al.*,
Phys. Rev. Lett. 115, 172503 (2015)



Cross sections for the production of the N=126 nuclei

Notice: obvious energy dependence
$^{136}_{54}Xe + ^{198}_{78}Pt$ E_{lab}=760MeV no nuclei with N=126 were observed
PRC 99,04460

Population of nuclides with *Z*≥98 in multi-nucleon transfer reactions of $^{48}Ca + ^{248}Cm$

H. M. Devaraja, S. Heinz, et al.

Euro.Phys.J . A February 2019 55:25

The nuclei above curium, produced in multi-nucleon transfer reactions of $^{48}Ca + ^{248}Cm$ at the velocity filter SHIP of GSI Darmstadt, Spontaneous fission and α -activities have been used to study the population of nuclei with lifetimes ranging from few milliseconds to several days.

Several relatively neutron-rich isotopes with *Z*≥98 were observed including a weak 224 millisecond activity tentatively attributed to ^{260}No

It indicates multi-nucleon transfer reactions are a way to reach new neutron-rich heavy and superheavy nuclei, which are not accessible in other reactions.

Theoretical approaches for study multi-nucleon transfer

1) GRAZING code

This code considers the multi-step exchange of nucleons between the colliding nuclei in classical trajectories calculated with a Coulomb plus nuclear interaction

A.Winther, NPA 572(1994)191, NPA594(1995)203, PRC62(00)054611

Only useful for transfer $\Delta Z = -1 \text{ to } +2.$

for mult-nucleon transfer it underestimate the experimental data by orders of magnitude.

Good prediction for 0p , -1 proton transfer but underestimate cross sections for multi-nucleon transfer by orders of magnitude.

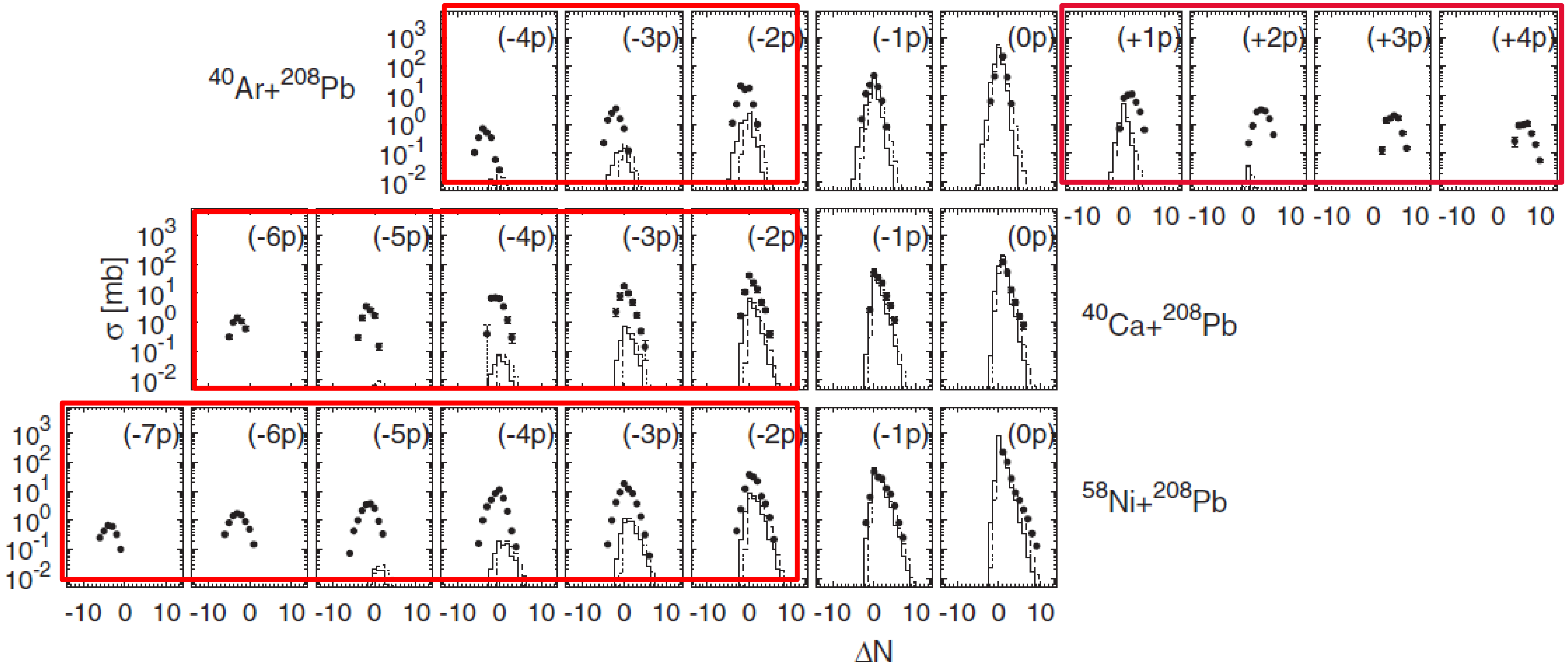
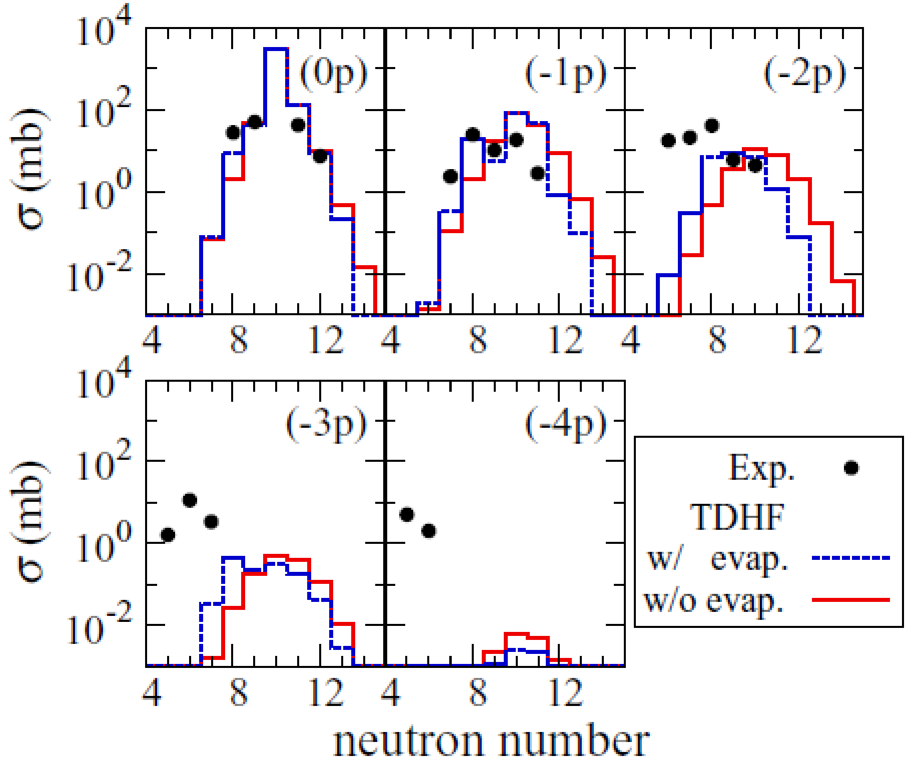


FIG. 7. Total experimental cross section for ^{40}Ar, ^{40}Ca, and ^{58}Ni induced reactions on the ^{208}Pb target, at beam energies $E_{\mathrm{lab}} = 6.4, 6.2$, and 6 MeV/A, respectively (points), and the GRAZING calculations with (solid line) and without (dashed line) neutron evaporation.

PHYSICAL REVIEW C **94**, 064616 (2016)

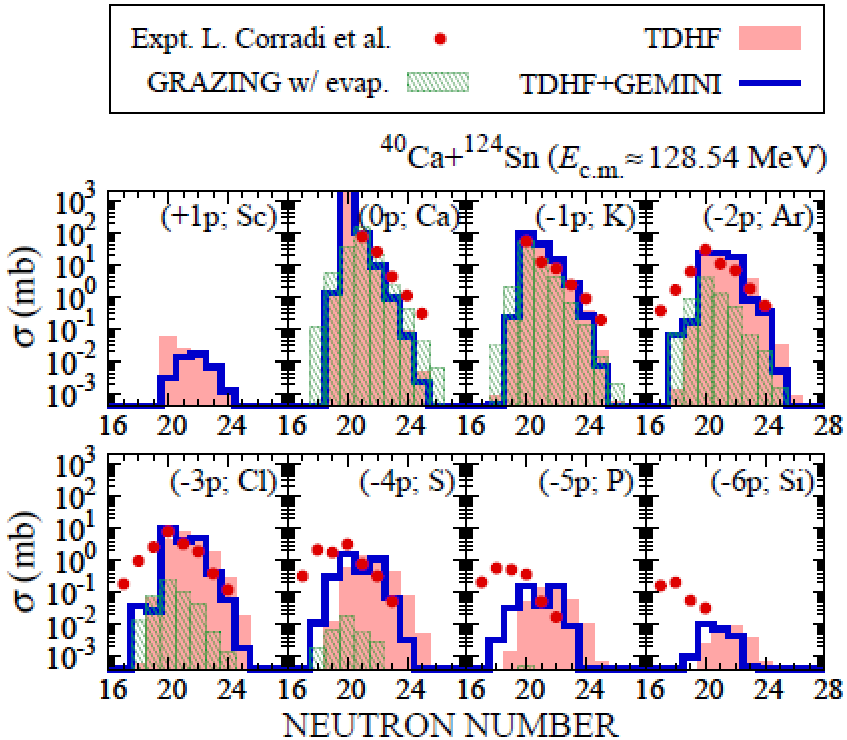
2）TDHF approach

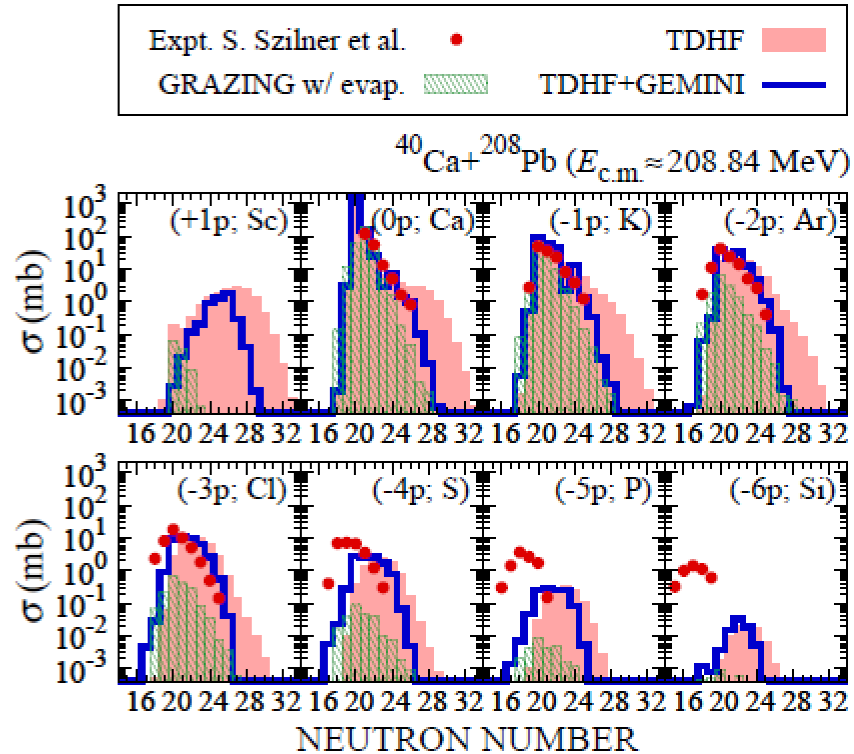
$^{18}O + ^{206}Pb$ reaction at $E(^{18}O) =$ 139MeV



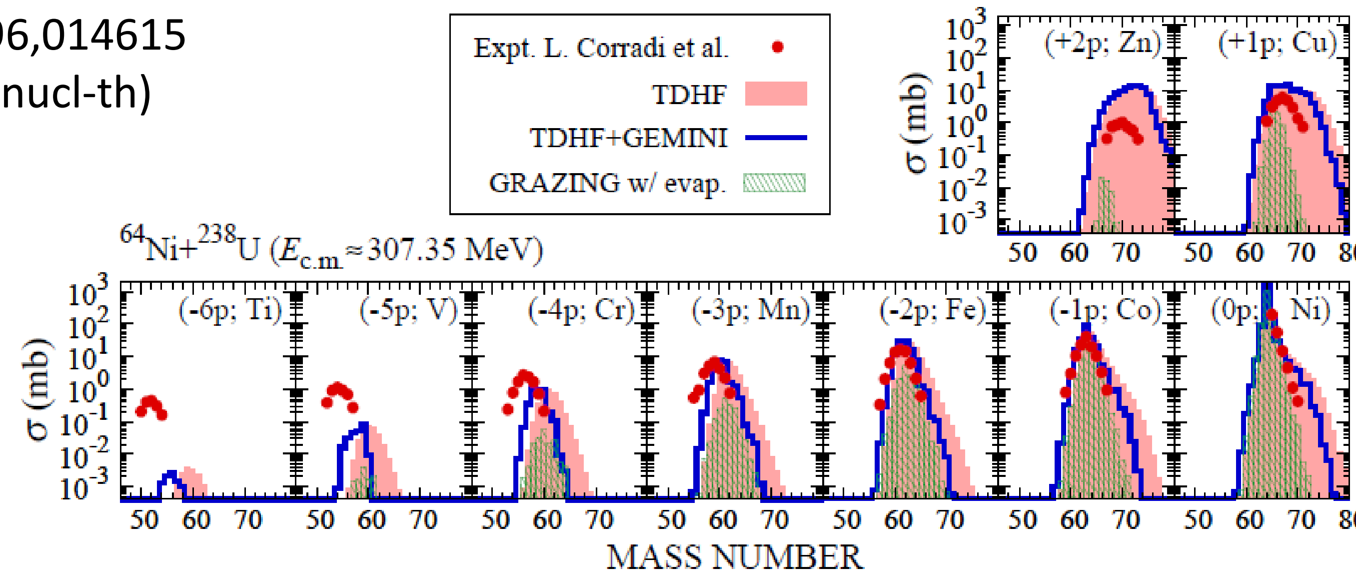
Reasonable prediction
For 0p,-1p transfer but
underestimate of the data
for multi-proton transfer
in orders of magnitude

PRC92(15)024603





K.Sekezawa, PRC96,014615
arXiv1705.02904(nucl-th)



3) Macroscopic dynamical model
- Coupled Langevin equations by Zagrebaev and Greiner

[17] V. I. Zagrebaev and W. Greiner, J. Phys. G: Nucl. Part. Phys. **35**, 125103 (2008).

[18] V. I. Zagrebaev and W. Greiner, Phys. Rev. C **83**, 044618 (2011).

[19] V. I. Zagrebaev, Y. T. Oganessian, M. G. Itkis, and Walter

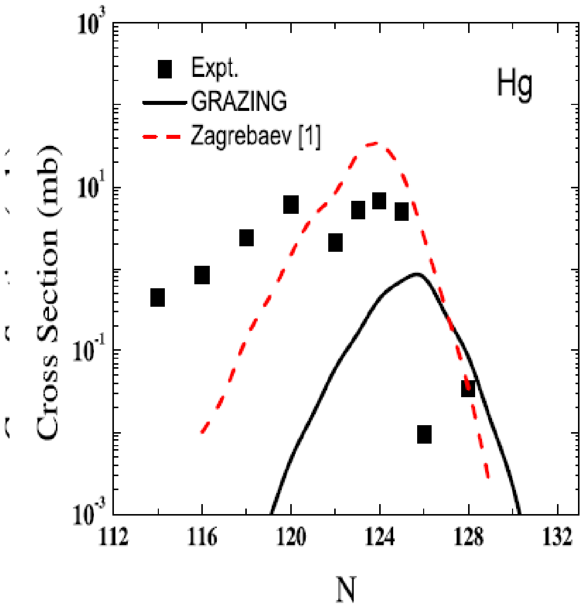
[20] V. I. Zagrebaev and W. Greiner, J. Phys. G: Nucl. Part. Phys. **34**, 1 (2007).

[21] V. I. Zagrebaev and W. Greiner, Nucl. Phys. A **834**, 366c (2010).

[22] V. I. Zagrebaev and W. Greiner, Phys. Rev. C **87**, 034608 (2013).

$^{136}Xe + ^{208}Pb$ reaction

Dubna PRC **86, 044611 (2012)** **only A , no Z measured**



II. Systematic studies of multi-nucleon transfer reactions with ImQMD model

The quantum molecular dynamics model

A-body dynamics , semi-classical microscopic approach

- many-body correlation and fluctuation are included
- Large number of degrees of freedom can be considered automatically

excitation, deformation of projectile and target, neck formation, nucleon transfer, different types of separation of composite system, nucleon emission

- The improved version of QMD is adopted

The Skyrme potential energy density functional is applied with readjusted parameters by fitting the properties of finite nuclei and nuclear matter, proper initial condition and Pauli-blocking

the ImQMD model

1. Each nucleon is described by a Gaussion wave pocket

$$\phi_i(\mathbf{r}) = \frac{1}{(2\pi\sigma_r^2)^{3/4}} \exp\left[-\frac{(\mathbf{r}-\mathbf{r}_i)^2}{4\sigma_r^2} + \frac{i}{\hbar}\mathbf{r}\cdot\mathbf{p}_i \right].$$

2. The motions of centroids of wave packets are described by

$$\dot{\mathbf{r}}_i = \frac{\partial H}{\partial \mathbf{p}_i}, \quad \dot{\mathbf{p}}_i = -\frac{\partial H}{\partial \mathbf{r}_i}.$$

$$H = T + U_{\mathrm{loc}} + U_{\mathrm{Coul}}, \quad U_{\mathrm{loc}} = \int \boxed{V_{\mathrm{loc}}[\rho(\boldsymbol{r})]} d\boldsymbol{r}.$$

potential energy density functional:

$$\boxed{V_{\mathrm{loc}} = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\gamma+1}\frac{\rho^{\gamma+1}}{\rho_0^{\gamma}}} + \boxed{\frac{g_{\mathrm{sur}}}{2\rho_0}(\nabla\rho)^2 + \frac{C_s}{2\rho_0}(\rho^2 - \kappa_s(\nabla\rho)^2)\delta^2 + g_\tau \frac{\rho^{\eta+1}}{\rho_0^{\eta}}}$$

3. In collision part, Pauli blocking (Uhling Uhlenbeck factors) is considered

4. Proper initialization of projectile and target

The reaction mechanism evolves with the size of reaction systems

Three systems are studied

Intermediate size system
$^{86}Kr+^{64}Ni$ at 25MeV/n

understanding the competition between fusion, elastic-inelastic , deep-inelastic and multifragmantation processes

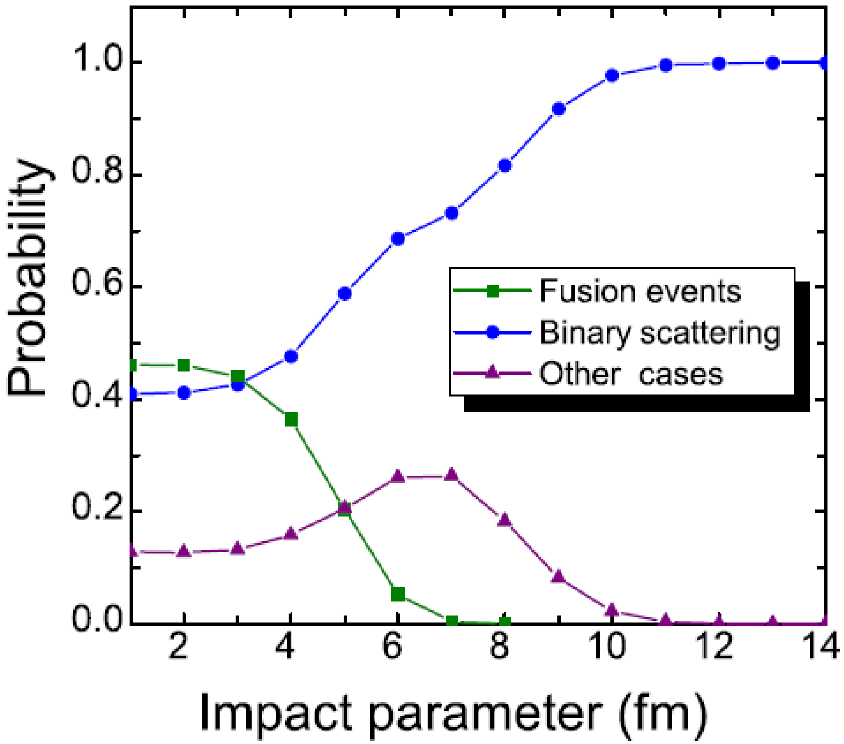
Neutron-rich
rare-earth region
$^{154}Sm+^{160}Gd$
at Ecm=440MeV

Show the efficiency of MNT on the production of neutron-rich nuclei Z=58-76,neutron-rich reaction system

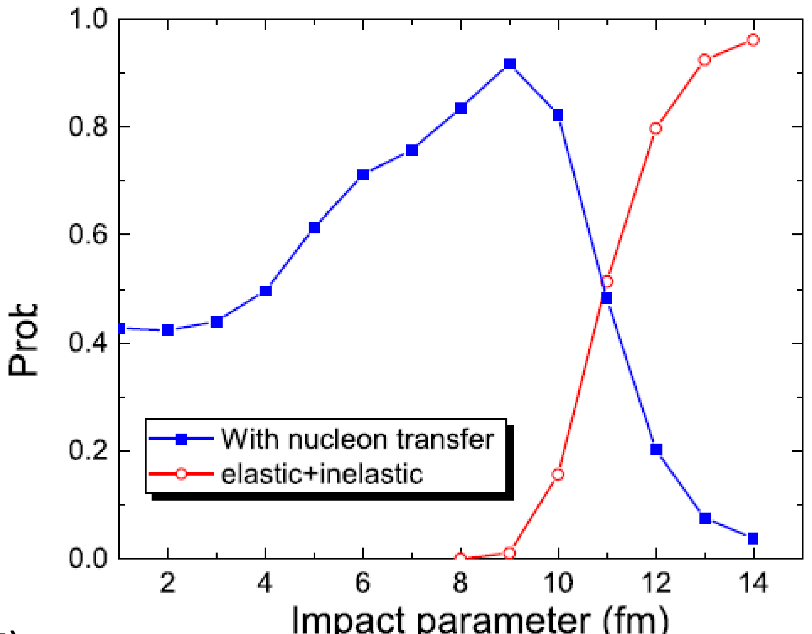
Actinide nuclei
$^{238}U+^{238}U$
at 7 MeV/n

Fusion is completely forbidden due to strong Coulomb repulsion
Study production of neutron-rich transuranium and light U-like Isotopes by MNT

Studies of the reaction $^{86}Kr+^{64}Ni$ at 25MeV/n



Reaction mechanism evolves with impact parameters
fusion: small impact parameter
Binary process: elastic, inelastic, MNT
Others: ternary breakup
and multifragmentation, etc



Binary scattering:
Elastic+inelastic (peripheral)
Deep inelastic(MNT)(peak at 8-9fm)

N. Wang , etal. Phys.Rev.C 95,014607(2017)

$^{86}Kr+^{64}Ni$ 25MeV/n

Mass-TKE correlation

Reaction mechanism evolves with impact parameters

Central collision: a highly excited composite system, small TKE →

fusion, MNT,

ternary breakup

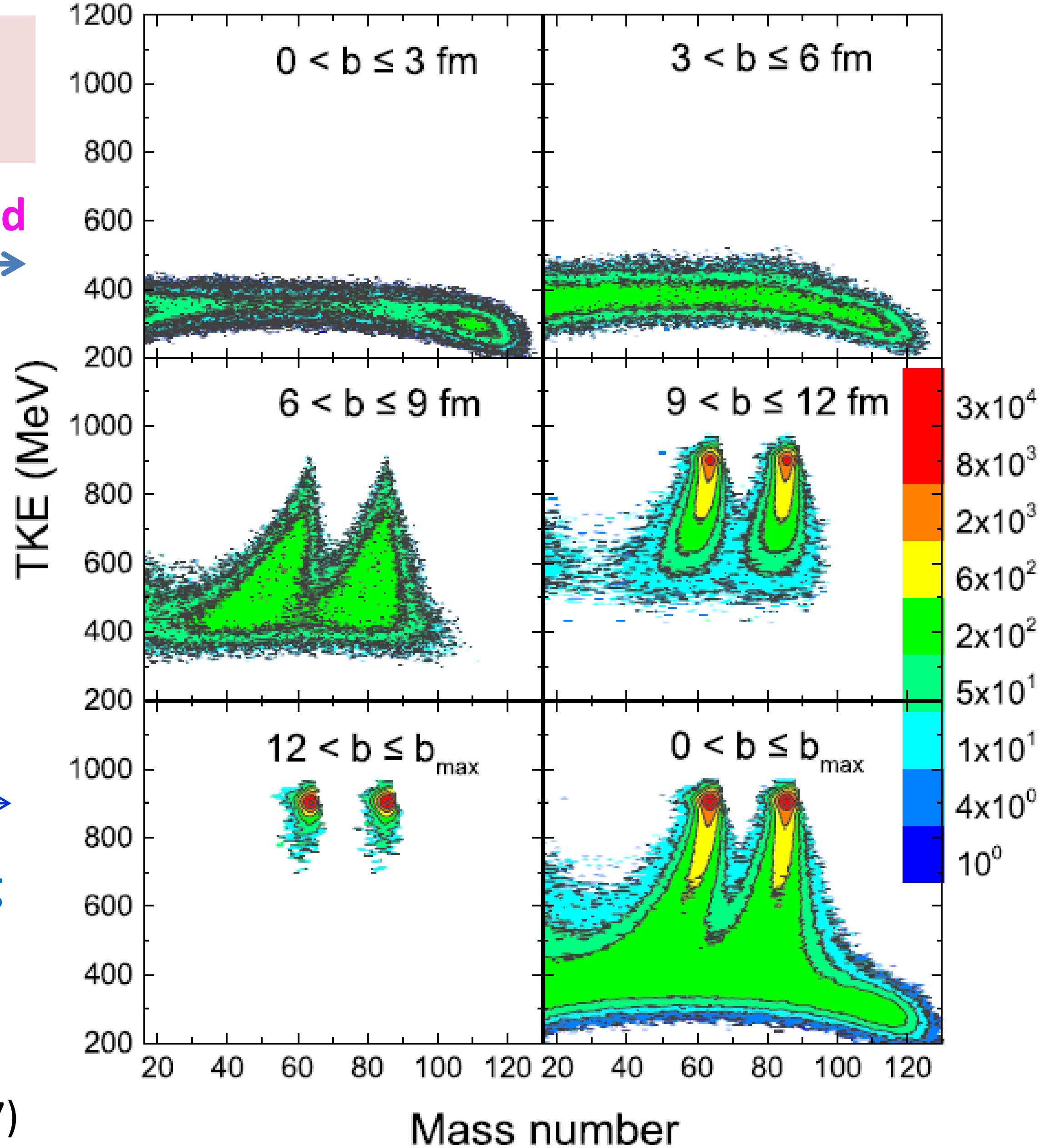
multifragmentation

MNT dominate →

Peripheral collision: →

Large TKE

Elastic and inelastic scattering

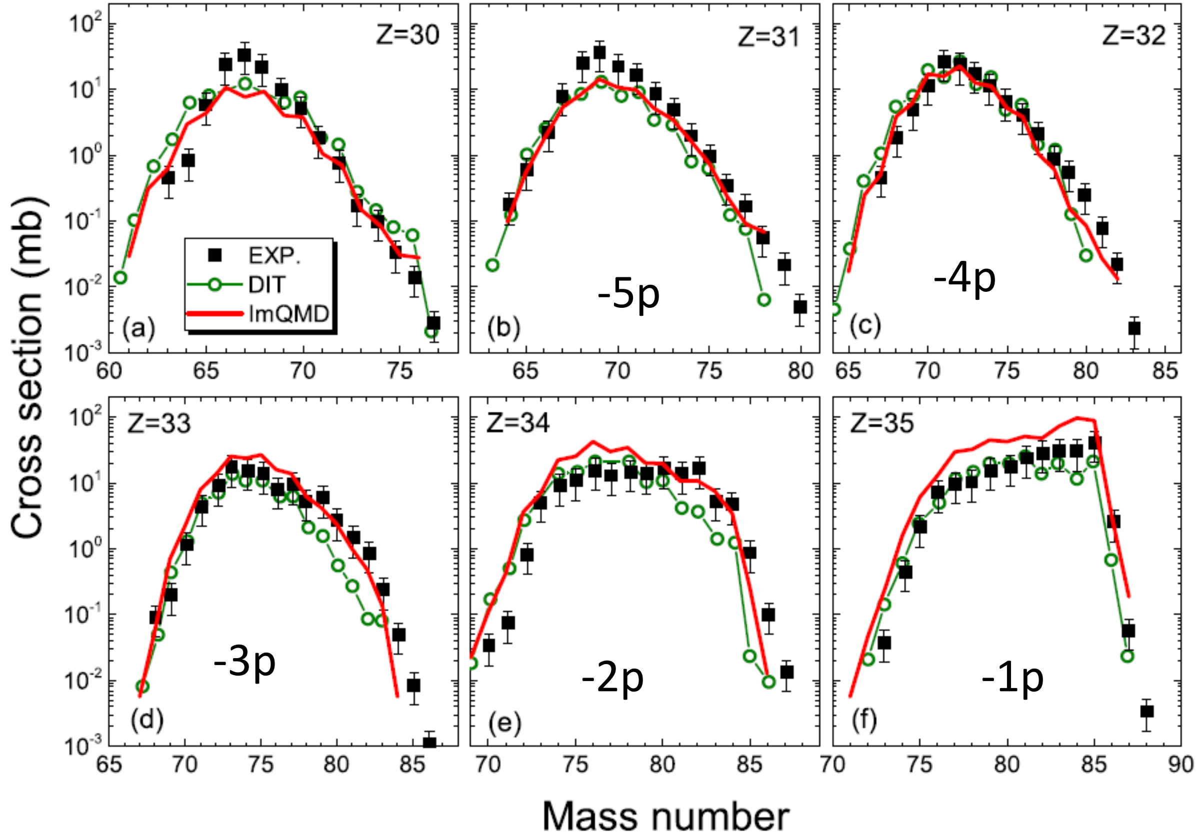


N. Wang Phys.Rev.C 95,014607(2017)

Cross sections of proton removal and neutron pickup isotopes

ImQMD +GEMINI calculation

$^{86}Kr+^{64}Ni$ at 25MeV/n

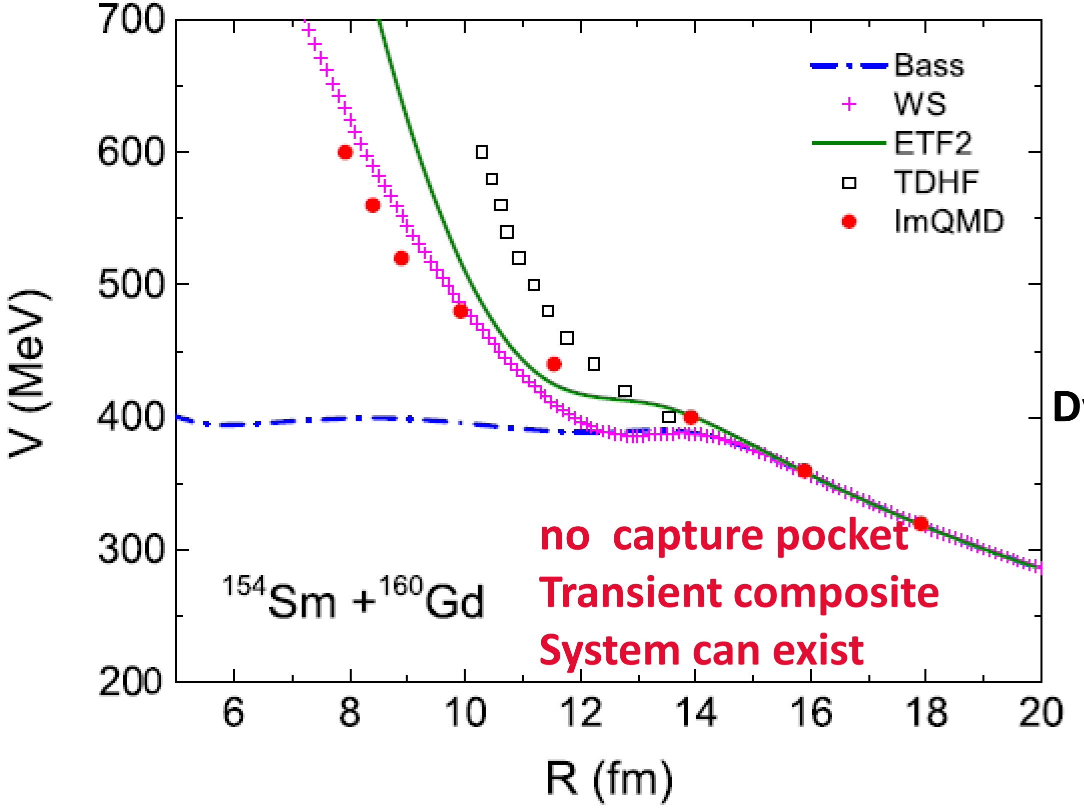


N. Wang , Phys.Rev.C 95,014607(2017)

Exp. Data and DIT/Germini from G.A. Souliotis et.al Phys.Lett. B543,163

MNT in ^{154}Sm+^{160}Gd at Ecm=440MeV, production of unknown neutron-rich isotopes

no fusion, MNT dominant at small impact parameters



WS: woods-Saxon pot. parametrization given by Broglia and Whinther

ETF2(given by Ning Wang,et.al.)

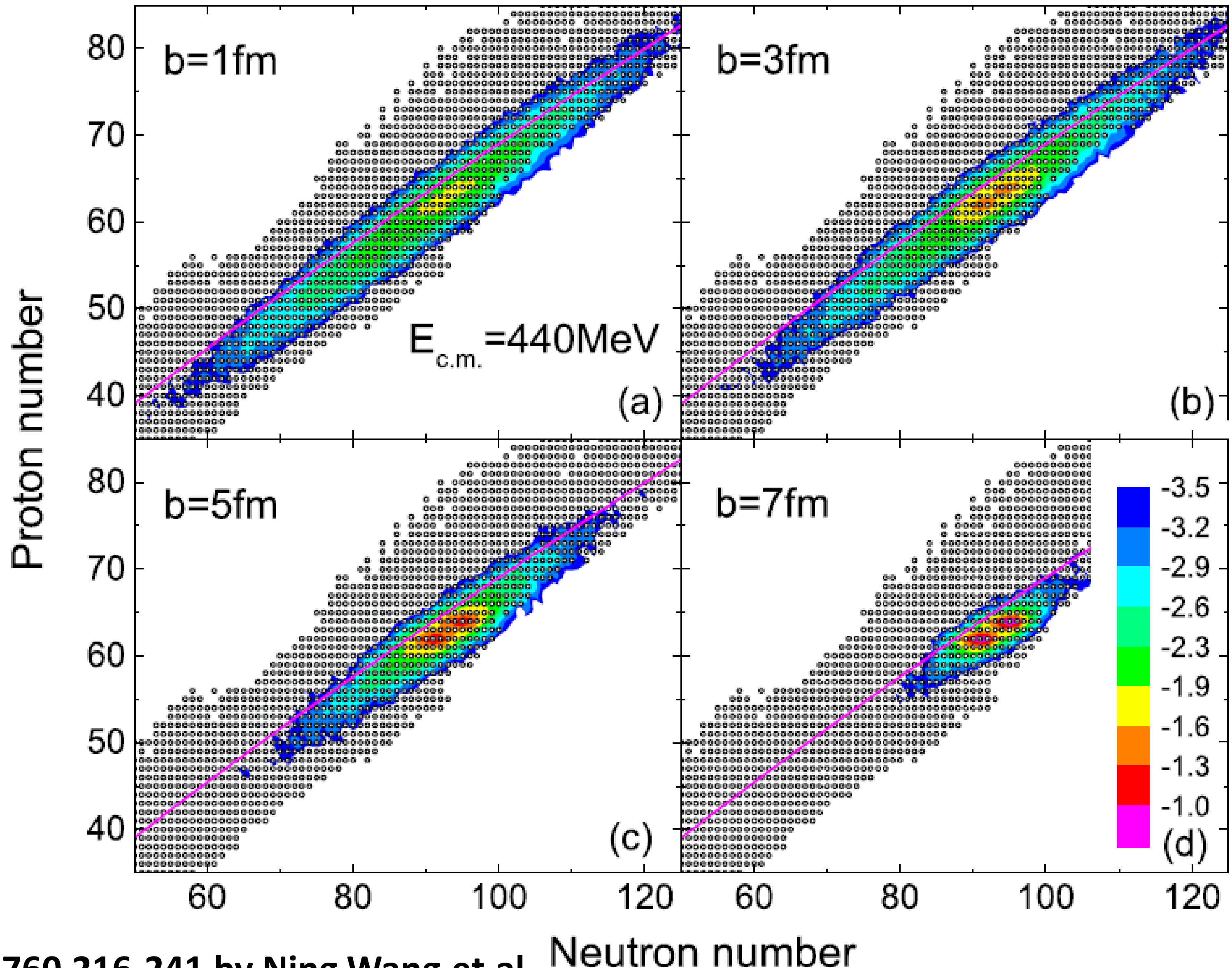
Dynamical pot. given by TDHF and ImQMD

$$V(R) \simeq E_{\mathrm{c.m.}} - T(R).$$

Nucleus-nucleus potential

PLB 760,216-241 by Ning Wang,et.al.

Primary fragments(ImQMD t=2000fm/c)



PLB 760,216-241 by Ning Wang,et.al.

cross sections of neutron-rich new isotopes (Z=58-76)

(ImQMD+GEMINI)

^{154}Sm+^{160}Gd at Ecm=440MeV

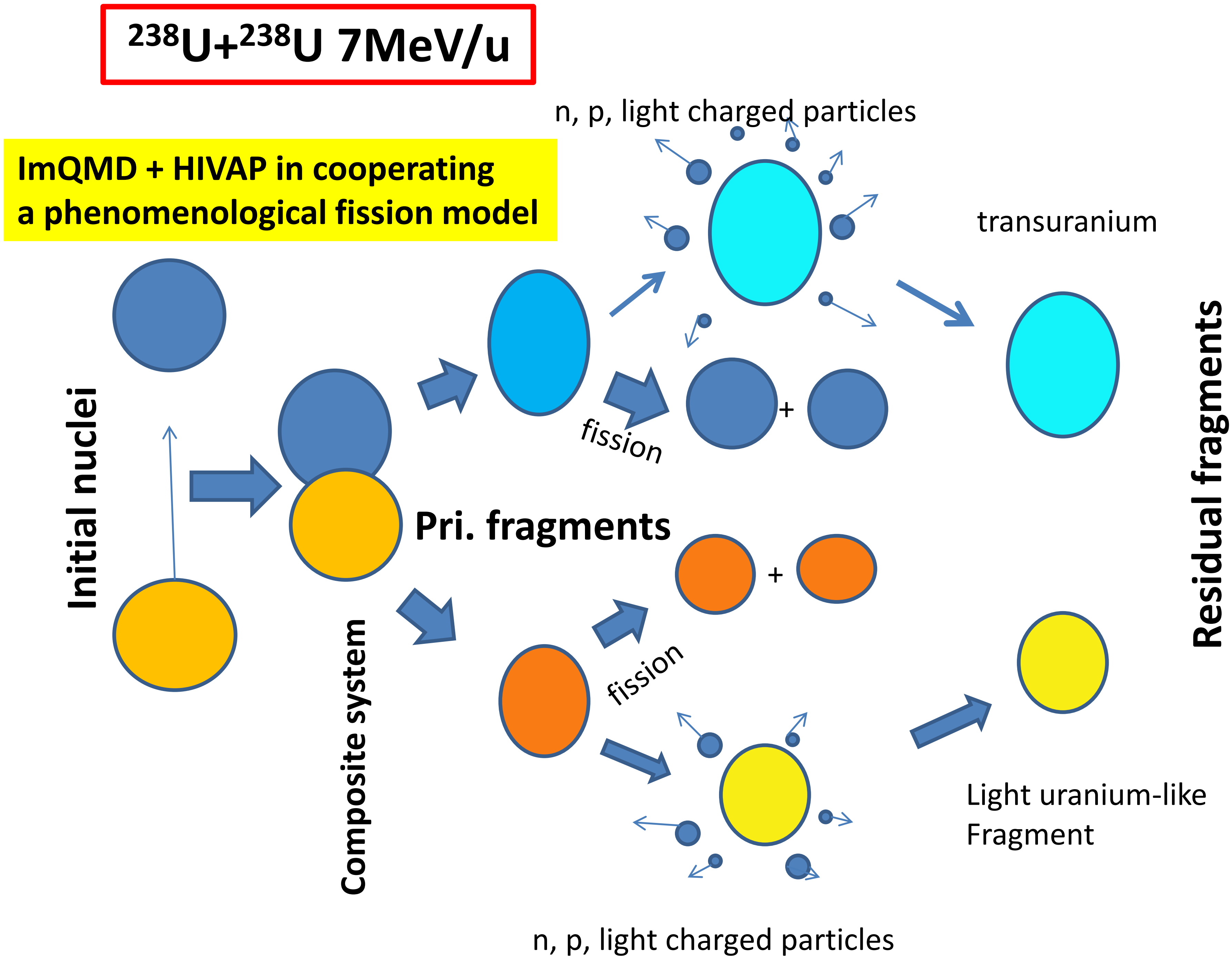
High efficiency!

Table 1

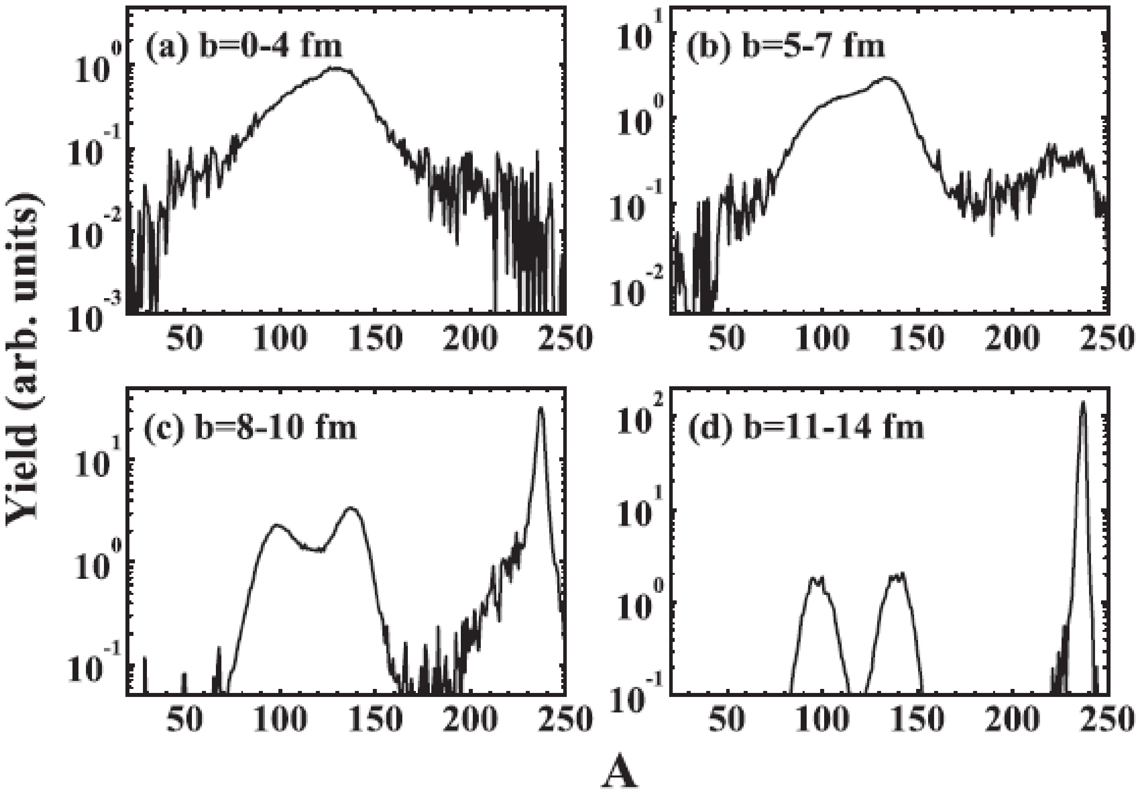
Production cross sections of some neutron-rich nuclei with unmeasured masses. The predicted mass excesses of these nuclei from the WS4 model [67] are also listed.

Z	N		$\sigma\,(\mu b)$	Mass excess (MeV)	Z	N		$\sigma\,(\mu b)$	Mass excess (MeV)
58	94	-4p, +2n	65	−59.33	68	105		975	−53.77
62	100	0p, 8n	31	−54.52	68	106		549	−52.31
63	101	1p, 9n	256	−52.74	68	107		96	−48.81
63	102	1p, 10n	54	−50.36	68	108		186	−46.89
64	100		1543	−59.72	68	109		100	−42.98
64	101		339	−56.29	68	110		44	−40.63
64	102		194	−54.48	69	108		316	−47.63
64	103		104	−50.62	69	109		92	−44.28
65	100		3288	−60.40	69	110		35	−42.02
65	102		806	−55.82	70	109		463	−46.71
65	103		140	−52.53	70	110		186	−44.99
65	104		161	−50.30	70	111		195	−41.38
65	105		46	−46.41	70	112		46	−39.36
66	104		469	−53.98	71	111		153	−41.77
66	105		130	−50.18	71	113		59	−36.45
66	106		117	−47.99	73	105	9p,7n	1639	−50.32
67	105		656	−51.40	73	116	9p,24n	138	−32.46
67	106		203	−49.33	75	119	11p,27n	54	−27.29
67	107		145	−45.76	76	121	12p,29n	180	−25.08

PLB 760,216-241 by Ning Wang,et.al.



$^{238}U+^{238}U$ 7MeV/u
ImQMD + HIVAP in cooperating
a phenomenological fission model
n, p, light charged particles
transuranium
Initial nuclei
fission
+
Pri. fragments
Composite system
+
fission
Residual fragments
Light uranium-like
Fragment
n, p, light charged particles



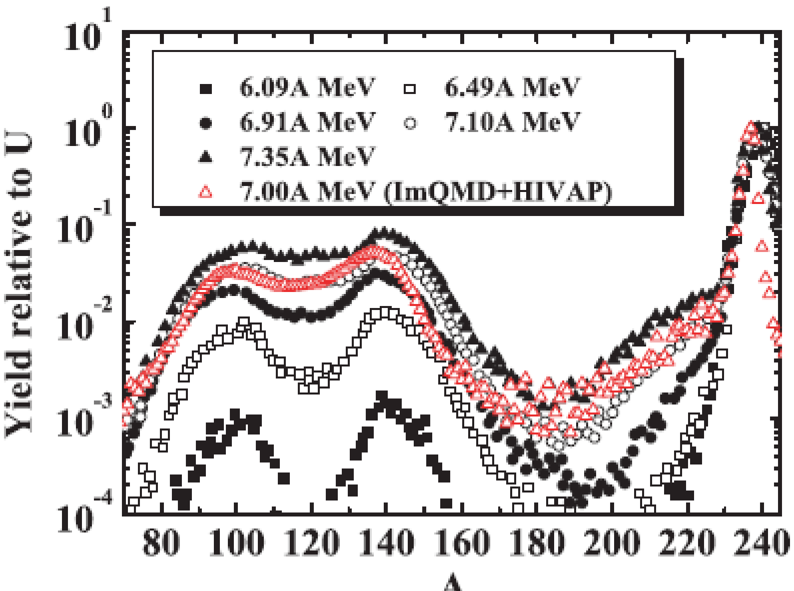
Mass distribution of products at different impact parameter region

a) large hump near A=120 high excitation, symmetric fission and a shoulder near Pb

b) Broad hump with mass $80 \leqslant A \leqslant 170$, superposition of symmetric and asymmetric fission, a small hump near A=230, in between is products near Pb

c) Following the decrease of excitation asymmetric fission increases, a small shoulder near Pb is shown

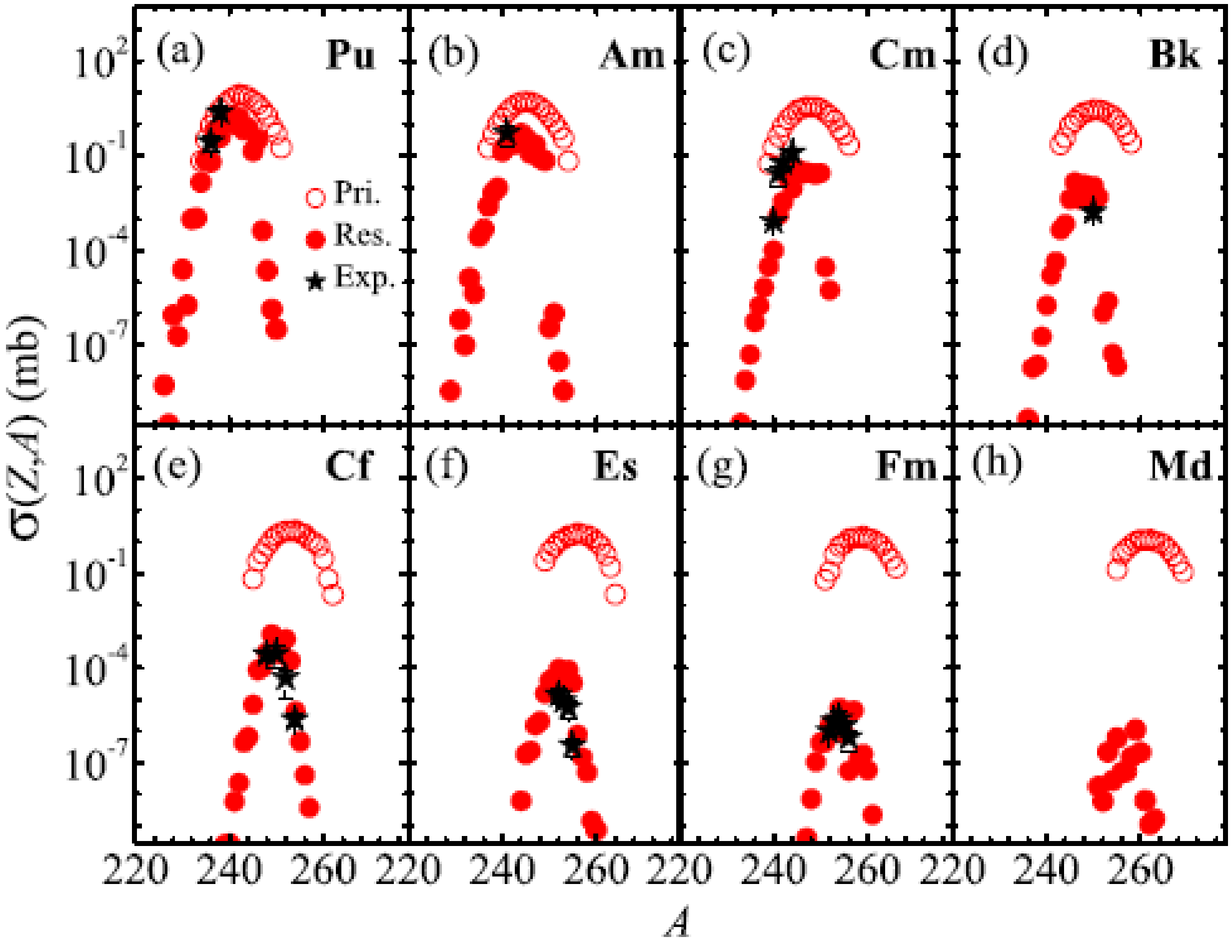
d) Low excitation energy, asymmetric fission, elastic(inelastic) scattering



Mass distribution of products
$^{238}U + ^{238}U$ at 7 MeV/n

PRC80 054607(2009)

Production of transuranium isotopes



Z=94-101

Features :
Magnitude of cross sections of primary fragments does not change much, residual fragments decreases exponentially with Z

The most probable residual fragments shift to more less neutron isotopes compared with that of primary fragments as Z increases

K.Zhao, Z.Li, N.Wang, Y.Zhang, Q.Li, Y.Wang, X.Wu, PRC **92, 024613 (2015)**

Exp.data : Phys. Rev. C 88, 054615 (2013)and references there in

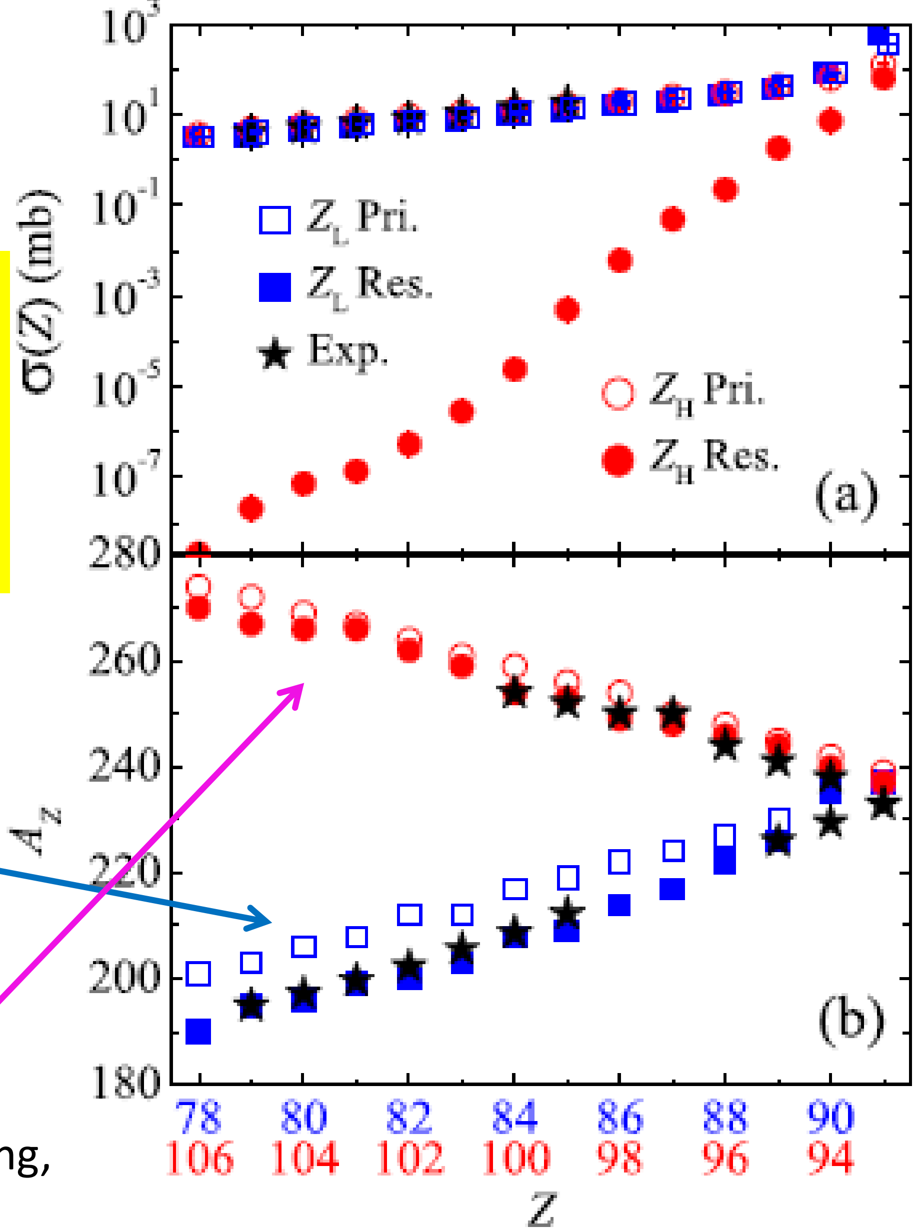
Comparison with experimental data

$\sigma(Z)$ **Production cross section of primary and residual fragments with charge Z**

light uranium-like fragments
$\sigma(Z)$ primary and residual similar
transuranium fragments
residual fragments decreases exponantialy

A_Z **The mass number of the most probable primary and residual fragments**

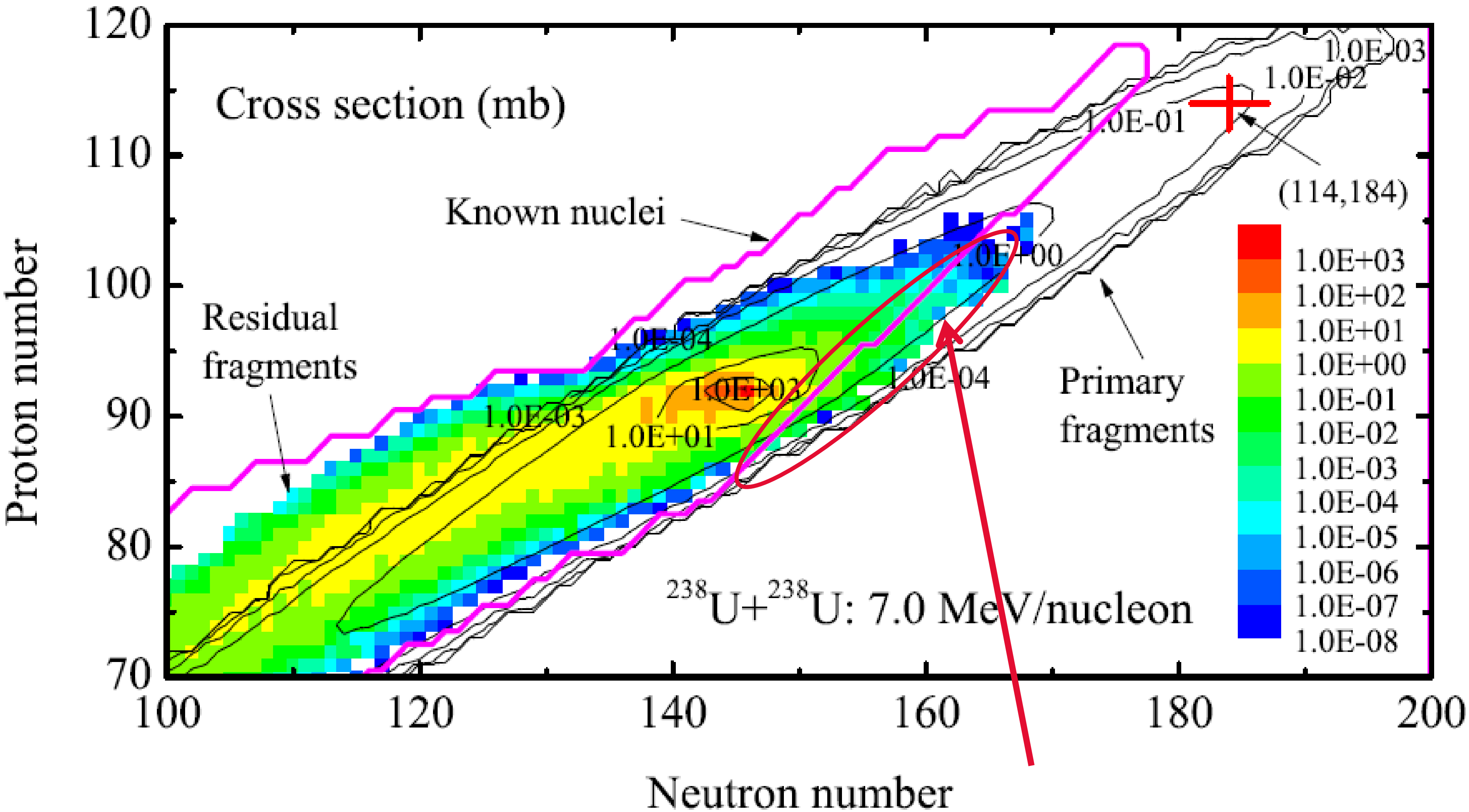
Light uranium fragments
Az pri. fragments is larger than residual fragments
Transuranium fragments Az pri. and resi. Fragments are close



K. Zhao, Z. Li, N. Wang, Y. Zhang, Q. Li, Y. Wang, X. Wu,PRC **92, 024613 (2015)**

Exp.data : Phys. Rev. C 88, 054615 (2013)

Produced primary and residual fragments in $^{238}U+^{238}U$ compared with known nuclei



K. Zhao, Z.Li, etc PRC94,024601

New neutron-rich transuranium nuclei

Better trand towards SHN

Key factors influencing the formation of residual fragments useful for finding best reaction system for synthesizing heavy neutron-rich transuranium isotopes

Peak isotopes of res.frag. ^{214}Rn, ^{249}Cf, and neutron -rich isotopes $^{254-256}$Cf

Cross sections of pri.frag.

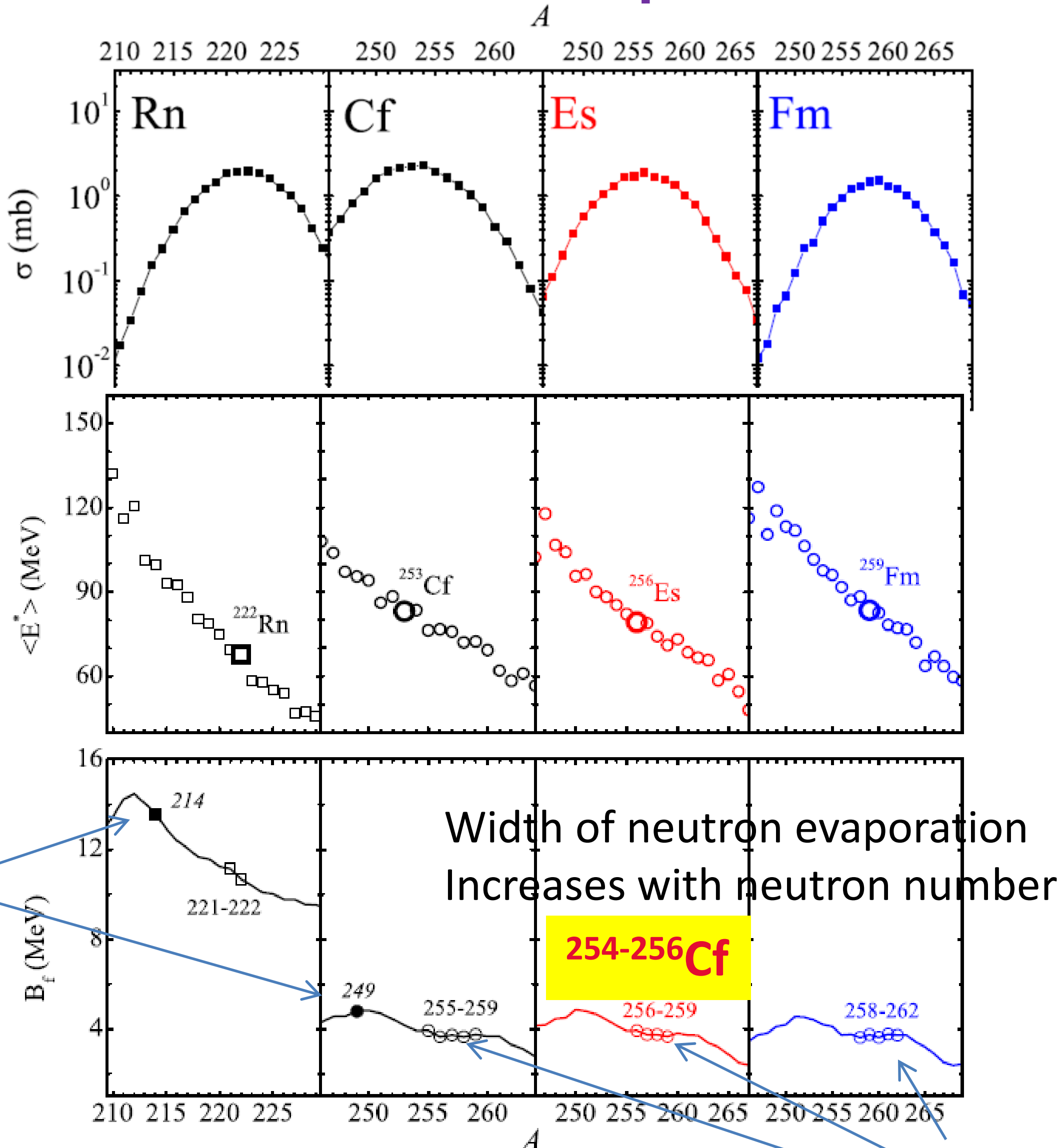
+

Excitation of pri.frag.

+

Isotope distribution of fission barrier

Competition between fission and evaporation neutrons



Conclusion from the study of MNT by ImQMD calculations

The HI reaction mechanism evolves with reaction system size, energy and reaction impact parameters

- The study of MNT reaction with $^{86}Kr+^{64}Ni$ at 25MeV/n shows its competitions with fusion, elactic-inelastic, MNT, and multi-fragmentation.

- The MNT reactions of neutron-rich nuclei are highly efficient for producing new neutron-rich nuclei ($^{154}Sm+^{160}Gd$,$^{238}U+^{238}U$)

- Study of U+U indicate isotope distribution of fission barrier is one of key factors that influence the formation of neutron-rich transuranium nuclei in addition to the cross sections and excitation energy of pri. Fragments. Importance of study isotope distribution of fission barrier It will be useful for finding the best reaction systems and energy for synthesizing extreme neutron-rich transuranium nuclei nuclei and possibly the SHN.

III. Discussions

Projectile-like fragments

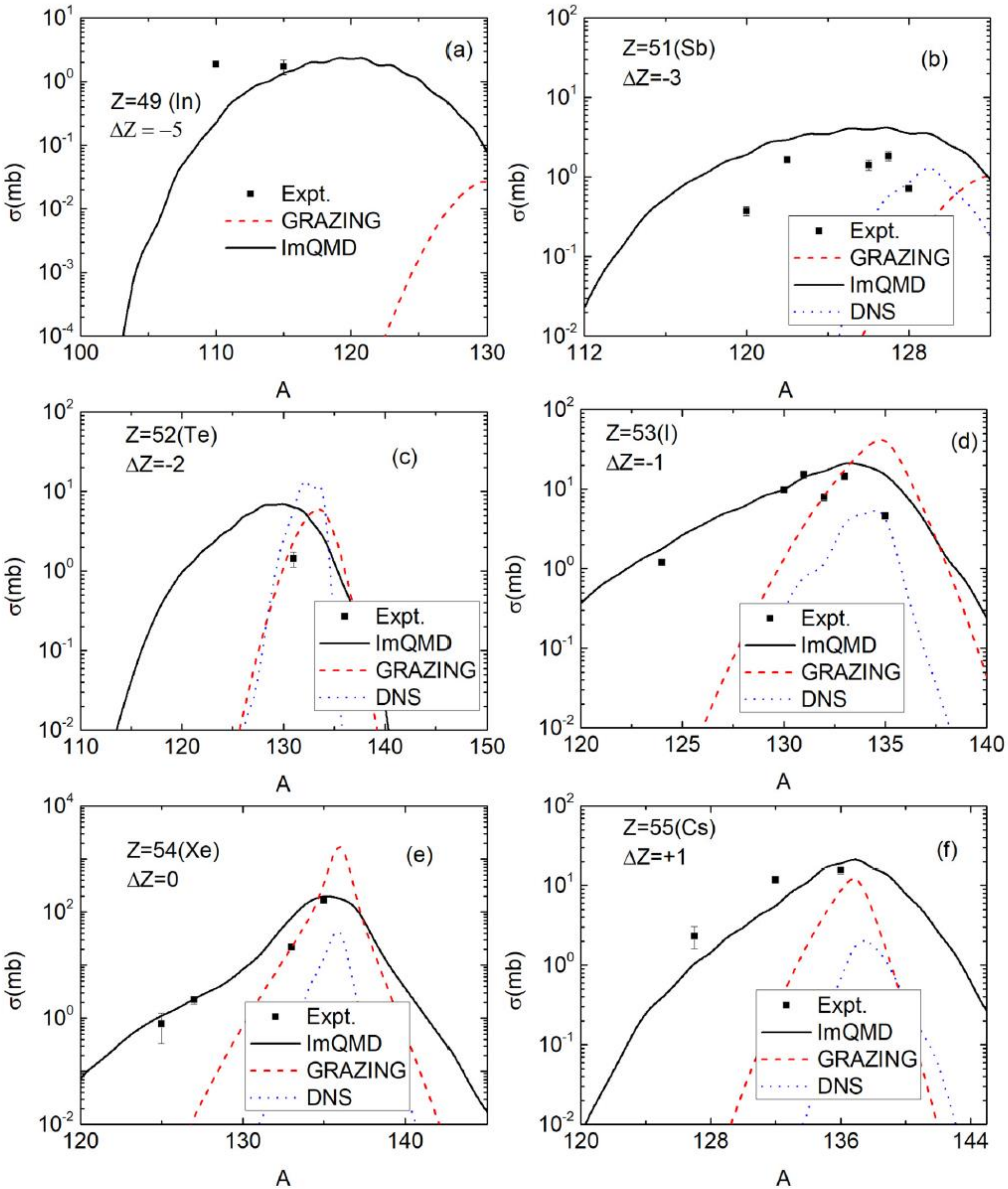
The 136Xe + 198Pt reaction:
a test of models of multi-nucleon
Transfer reactions

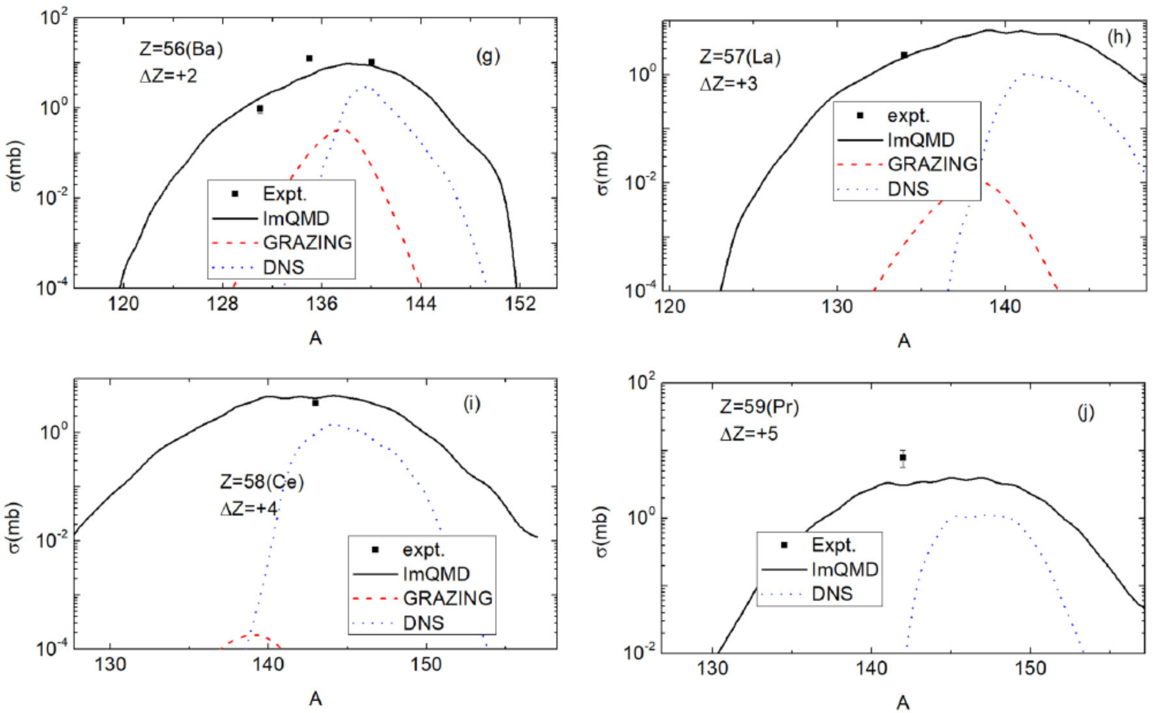
PRC99,044604(2019)

$$\Delta Z = -5 \text{ to } +17 \text{ for PLFs}$$

$$\Delta Z = -6 \text{ to } +6 \text{ for TLFs}$$

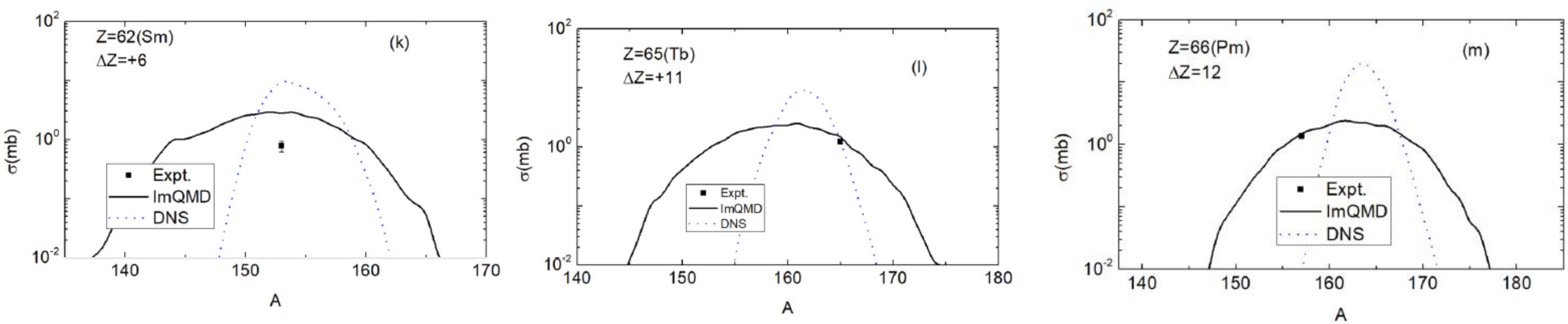
Experimental measurements results
Compared with three model calculations
Grazing,DNS, and ImQMD





Projectile-like fragments

PRC99,044604



PRC99,044604

Comparing the measured and calculated Cross sections of products

$$\mathrm{tef}_i = \log\left(\frac{\sigma_{\mathrm{theory}}}{\sigma_{\mathrm{expt}}}\right)$$

$$\overline{\mathrm{tef}} = \frac{1}{N_d}\sum_{i=1}^{N_d}\mathrm{tef}_i,$$

ImQMD

average tef value -0.00893 ± 0.084;

i.e., misestimate factor of 0.98

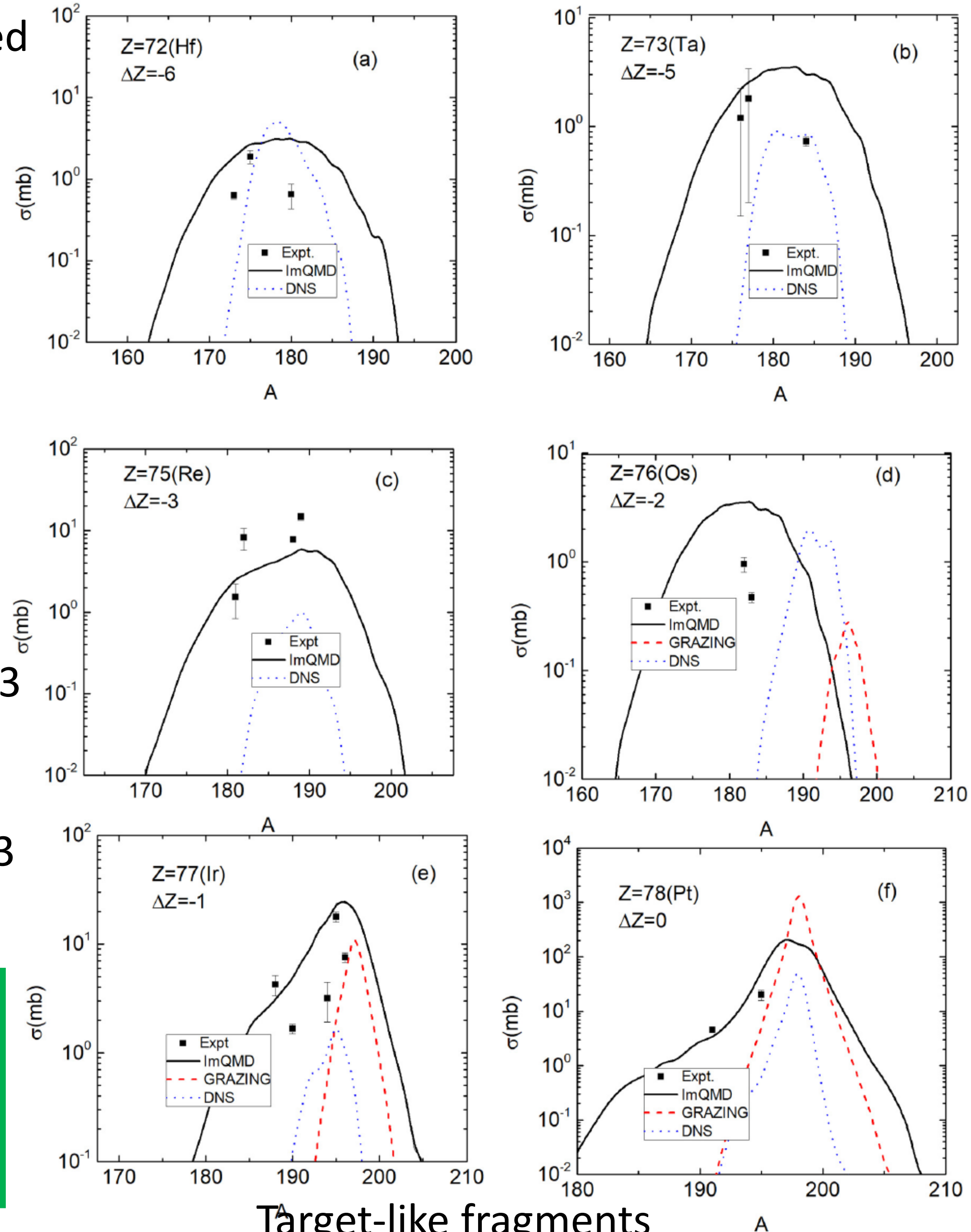
Grazing model

-1.353 ± 0.044 Underestimate factor 23

DNS model

-1.724 ± 0.211 Underestimate factor 53

DNS and grazing model is not dynamical and simple ,
dynamical study is Important for better description of MNT reactions



Target-like fragments

Description with TDHF and ImQMD are both dynamical
From the studies of MNT reactions with the TDHF(without initial fluctuation) and ImQMD (with initial fluctuation) calculations, it makes us to understanding following three points

1) Fluctuation plays important role for multi-nucleon transfer channels, the initial fluctuation should be carefully considered.

2) It is recognized that the reactions between two heavy nuclei at near or above barrier are strong dissipative. In ImQMD calculations both one and two body dissipation are considered, while TDHF is a mean field approach. Two approaches may have different dissipation. Stronger dissipation helps two nuclei to be stick together longer time, which helps multi-nucleon transfer.

3) Shell effect plays an important role in some cases for example , in near shell closing nuclei. TDHF approach can do better.

Thanks for attention